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"Global Magnetospheric Ion Dynamics"

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Summary of Research

This project was an investigation of ion dynamics in the Earth's magnetosphere focusing primarily on the entry of ions into the magnetosphere. The methodology was to calculate the trajectories of many ions (thousands), according to the technique of large scale kinetics (LSK), in the electric and magnetic fields from snapshots of global magnetohydrodynamic (MHD) simulations for different interplanetary magnetic field (IMF) conditions. By studying the behavior and statistics of these ions it is possible to determine the mechanisms of their entry into the magnetosphere. The results of this study showed that the global magnetospheric configurations from the MHD calculations controlled the overall entry sites and mechanisms through the geometry of magnetic reconnection. In the entry regions determined by the global geometry the efficiency of the entry and energization process was determined by guiding center drifts, non-adiabatic particle dynamics and other non-MHD physics. An interplay between the global field geometry and local particle processes determined the distribution and energies of magnetospheric particles in our model. The results of this study imply that if non-fluid ion dynamics could be included in global magnetospheric models it would be a breakthrough in their predictive capability.

In our calculations the particles (ions) were launched at an array of points in the solar wind $20R_E$ sunward of the Earth. Their trajectories were then followed until they either exited the outer boundaries of the calculation domain (typically from $20R_E$ upstream of the Earth to $60R_E$ tailward and $40R_E$ from the Earth in the dusk, dawn, north and south directions) exited the inner boundary at $6R_E$ from the Earth (just outside the inner boundary of the global MHD simulation at $5.5R_E$ from the Earth), or remained in the simulation system for too long a time (several hours) for the quasi-steady state approximation to be valid. Information about particles was recorded when they cross planes in the simulation system that are defined as "virtual detectors". In our coordinate system x pointed tailward, y was dawnward and z was northward.

During this investigation we focused mainly on three IMF orientations: a northward IMF case, a southward IMF case and a case with southward IMF including a B_y component. The cases are all the subject of ongoing analysis, but the major physical processes affecting the particles are now fairly well understood.

The northward IMF case was run until a quasi-steady state was reached. This state was characterized by reconnection between magnetospheric and solar wind field lines tailward of the cusp. Almost all particles that entered the magnetosphere in this case do so when the solar wind field lines with which they are convecting reconnect at high latitudes. If they encounter the reconnection region tailward of the cusp they are energized by traveling along the cross polar electric field in the region of weak reconnecting magnetic field, with those particles nearest the reconnection region gaining the most energy. The most energetic of these experienced low values of κ, defined as the square root of the ratio of the field line curvature to the Larmor radius of the particles, reflecting non-adiabatic acceleration mechanisms. Most of these particle entered on the dawn side, even though the MHD simulation is symmetric about $y = 0$, because the gradient drift on the dayside was dawnward and because particles that were accelerated along the electric field travel toward dawn. The particles that entered the magnetosphere bounced on closed field lines inside of the magnetopause while convecting tailward to form the low latitude boundary layer (LLBL) on the dawn side. Some of these particles became trapped and circle the Earth under the influence of gradient and curvature drifts. Others spread out across the magnetotail to form the plasma sheet, and drifted toward the dusk side while convecting tailward. Because of the stronger magnetic field near the noon-midnight meridian, particles bounced closer to the equator there than at the flanks giving the plasma sheet a "butterfly" shape in planes at constant x.

In the southward IMF case the IMF had been northward and was then turned to a purely southward direction, causing reconnection on the dayside. The MHD snapshot used was for a magnetosphere in a state simulating the growth phase of a substorm. Tail reconnection has not yet begun.

In the southward IMF case, most particles enter the magnetosphere through the mantle. The mantle extends much lower in z on the dawn side because of parallel electric fields near the magnetopause. In the MHD simulation $\vec{E} = -\vec{v} \times \vec{B} + \eta\vec{J}$ where $\vec{E}$ is the electric field, $\vec{B}$ is the magnetic field, $\vec{J}$ is the current and η is the resistivity. Therefore parallel electric fields are associated with field aligned currents: $\vec{E} \cdot \vec{B} = \eta\vec{J} \cdot \vec{B}$. These field aligned electric fields lead to a potential drop across the magnetopause that attracts particles toward the magnetosphere on the dawn side and repels them on the dusk side. Mantle particles that reach the equatorial plane convected earthwards. Those that crossed the magnetotail toward the dawn were energized by the electric field. Some particles entered the tail through a zone of weak reconnection on the dusk side flank. A few particles became temporarily trapped. The entry rate of particles reaching the magnetotail midplane was comparable in the northward and southward IMF cases, with rates of $1.7 \times 10^{27} ions/sec$ calculated for the northward IMF case and $2.1 \times 10^{27} ions/sec$

for the southward IMF case. In the southward IMF case many more particles, $2.2 \times 10^{28} ions/sec$ entered the magnetosphere temporarily, mostly in the plasma mantle, but left the magnetosphere without reaching the equatorial plane. Only the lowest energy particles that reached the equatorial plane from the mantle. Higher energy ones, energized by the electric field on the dayside, were ejected by the mirror force or convected too slowly to reach the equatorial plane before their field aligned velocity took them out of the magnetosphere. There were LLBL layers visible on both dusk and dawn flanks. On the dawn side these were particles that entered the magnetosphere in the plasma mantle, then convected earthward from the magnetotail and were energized. The most energetic ones formed a partial ring current closer to the Earth. The dusk side LLBL consisted of hot particles that have entered the magnetosphere in the weak field region and particles that have convected from the dusk or dawn side of the magnetotail.

In a third major calculation, the IMF in the MHD simulation was also southward but with a B_y component that caused a flux rope to form in the magnetotail. In this calculation, particles entered the magnetosphere because of dayside reconnection, mainly on the dawn side. Many of these became briefly trapped on closed field lines before moving into the magnetotail. There these particles moved tailward on open field lines (opened by magnetotail reconnection) and reached the vicinity of the flux rope. They then moved onto twisted flux rope wind field. Interactions with the magnetotail reconnection electric field often energized these particles. Gradient and curvature drifts caused particles to move from the dawn to the dusk side of the magnetotail. Dusk side particles often convected back toward the Earth. The preponderance of magnetotail particles then left the magnetosphere on the dusk side.

There seems to be a coherent picture emerging in these results. Particles entered the magnetosphere on the dayside due to magnetic reconnection of the field lines they were convecting with. Guiding center drifts on the dayside favored dawn side entry. During the entry process they often interacted with the cusp. A southward component to the IMF (in a growth phase configuration) energized particles on the dayside but only the lowest energy ones entered the magnetotail through the mantle. Many particles reached open field lines but left the magnetosphere on them without entering the tail. A northward IMF resulted in lower overall entry rates but because of ubiquitous closed field lines in the magnetotail those particles that did enter typically remained in the magnetosphere for a longer time and underwent many more mirror bounces in the LLBL and the plasma sheet. These particles were usually energized during the entry process and tended to lose energy gradually in the tail. Entry from the mantle in the southward IMF case allowed only lower energy particles to reached the tail, but they may reach high energies there if they drifted across the tail. In the presence of a flux rope structure and southward IMF particles also entered the magnetosphere as the field lines they were on were opened by dayside reconnection, but unlike the purely southward IMF case they later underwent complex interactions with the flux rope. During these interactions they shifted towards the dusk side and eventually exited the magnetosphere. Ultimately this overall picture will be refined and further quantified, producing the systematic statistics of the entry process in various magnetosphere configurations.

There were no patents or inventions resulting from this grant.

Publications

Richard, R. L., R. J. Walker, and M. Ashour-Abdalla, The population of the magnetosphere by solar wind ions when the interplanetary magnetic field is northward, Geophys. Res. Lett., 21, 2455, 1994.

Walker, R. J., R. L. Richard, T. Ogino, and M. Ashour-Abdalla, Solar wind entry into the magnetosphere when the interplanetary magnetic field is southward, Physics of Space Plasmas (1995), SPI Conference Proceedings and Reprint Series, edited by T. Chang, in press 1996.

Invited Talks

Walker, R. J., R. L. Richard, T. Ogino, and M. Ashour-Abdalla, Ion entry into the magnetosphere, 1995 Cambridge Symposium/Workshop, Hamilton, Bermuda, February 20-25, 1995.

Contributed Talks

Richard, R. L., R. J. Walker, M. Ashour-Abdalla, and T. Ogino, Population of the magnetosphere for southward and dawnward IMF, Spring AGU Meeting, Baltimore, MD, May 1994 (EOS, 75, 299).

Richard, R. L., R. J. Walker, M. Ashour-Abdalla, and T. Ogino, Population of the magnetosphere for southward IMF, Fall AGU Meeting, San Francisco, CA, December 1994 (EOS, 75, 544).

Richard, R. L., R. J. Walker, T. Ogino, and M. Ashour-Abdalla, The entry of solar wind ions into the magnetosphere when the interplanetary magnetic field is southward, Spring AGU Meeting, Baltimore, MD, May 30 June 2, 1995 (EOS, 76, 252).

Richard, R. L., R. J. Walker, M .Ashour-Abdalla, and T. Ogino, Population of

the magnetosphere for different IMF orientations, 1995 IUGG Meeting, Boulder, CO, July 1995.

Richard, R. L., R. J. Walker, M. Ashour-Abdalla, and T. Ogino, Dusk-dawn asymmetry in magnetospheric ion entry, Fall AGU Meeting, San Francisco, CA, December 1995 (EOS, 76, F523).